THE RELATIONSHIP OF EPIPHYSIAL PLATES TO STRESS IN SOME BONES OF THE LOWER LIMB

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The plates of cartilage which separate the diaphyses from the epiphyses in immature bones have long been of interest to both anatomists and clinicians. This interest has centred, on the one hand, on their histology and the part which they play in the elongation of these bones during development, and, on the other, on the disturbances which may affect them in childhood and adolescence. However, the shapes and positions of individual epiphysial plates and the factors which determine these features have received comparatively little attention.

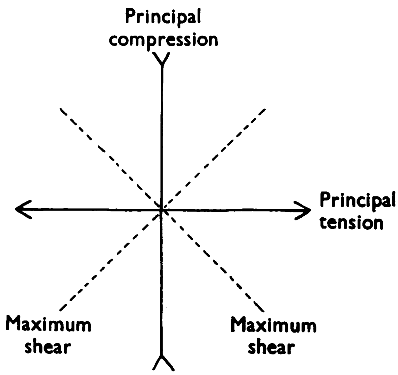
Following the work of Meyer (1867), Thompson (1942) and many others, it is widely accepted that the shape of a bone as a whole, and the disposition of the fine trabeculae within it, are in harmony with, and are probably in some measure determined by, the stresses experienced during normal activity. It seemed possible therefore, that an entity such as an epiphysial plate, which is an inherent part of a bone throughout a considerable part of active life, might bear a similar relationship to stress, and moreover that this relationship might explain the peculiar shapes of individual plates.

STRESS, STRAIN AND STABILITY

External forces acting on a body cause *stresses* within it. These internal stresses in turn cause changes, of varying magnitude and kind, in the dimensions of the body, and these changes are known as *strains*. Stresses within a body, and the resulting strains, may be of three kinds. A *compressive stress* is one which causes a diminution of the dimension along which it acts. A *tensile stress*, on the other hand, increases the dimension along which it acts. Thirdly, if the stressed body is considered as being composed of a large number of lamellae of minute width, a *shear stress* is one which causes relative displacement of these adjacent elementary lamellae along the intervening parallel planes.

Any external force inevitably causes all three types of stress, simultaneously, within an affected body. At any chosen point the compressive and tensile stresses are maximal in two orthogonal directions, and these maxima are designated the *principal stresses* at that point. Moreover, it can be shown that at the same point shear stress is zero in the directions of the principal stresses and maximal in directions at 45° to them. Thus the disposition of the three stresses at a point can be illustrated diagrammatically as in Text-fig. 1.

When a bone is subjected to external forces of any kind during activity, compressive, tensile and shear stresses are developed within it. It is evident that in an immature bone the stability of the epiphysis in relation to the diaphysis depends on the relationship of the epiphysial plate to the internal stress pattern. If the epiphysial plate conforms throughout its whole extent to the direction of one of the principal stresses, no shear stress will operate between the epiphysis and the diaphysis and the relationship between these parts will be stable. On the other hand, if this relationship does not exist, the forces exerted on the bone during activity will cause shear stress between the epiphysis and the diaphysis and will consequently tend to cause displacement of the one part upon the other. This principle was clearly stated by D'Arcy Thompson who wrote: 'In short, we see that, while shearing stresses can by no means be got rid of, the danger of rupture or breakdown under shearing stress is lessened the more we arrange the materials of our construction along the pressure lines and tension lines of the system; for along these lines there is no shear.'



Text-fig. 1. The disposition of the principal tensile and compressive stresses and the maximal shear stresses at a point.

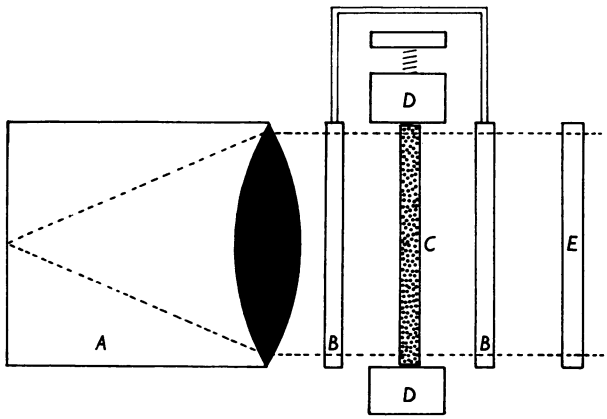
METHODS

The photoelastic method

This is a method by which the directions of the principal stresses can be determined throughout a thin sheet of a transparent solid when it is subjected to external forces. It is used extensively in industry and has been adapted to the problem of stresses in bones by Hallermann (1934), Milch (1940), Pauwels (1948, 1951) and Fessler (1957). The apparatus used in the method is illustrated in Text-fig. 2.

A light source (A) produces a wide parallel beam which traverses two polaroid plates (BB) and a ground-glass screen (E). The polaroid plates (BB) are 'crossed', that is the plane of vibrations which the first (the polarizer) transmits is at right angles to the plane of vibrations which the second (the analyser) is able to transmit. Consequently if nothing is interposed between the polarizer and analyser, the latter will transmit no light to the screen (E). The polarizer and analyser are coupled so that they may be rotated synchronously, and therefore in a permanently crossed relationship, about the centre of the light beam. (C) is a transparent solid, interposed between the polarizer and analyser, and mounted in such a way that it can be subjected to an external force (e.g. by the clamp DD).

The theory of the photoelastic method (Jessop & Harris, 1949) is not relevant to the present paper. It can be shown, however, that when a stressed transparent solid is interposed between the crossed polarizer and analyser light is transmitted to the screen through all parts of the solid except those at which the principal stresses are in alignment with the polarization planes of the polarizer and analyser. These regions appear as a series of dark lines known as *isoclinics*. Beginning from any chosen position, the polarizer and analyser may be rotated at 10° intervals through a range of 80° and the resulting nine sets of isoclinics may be traced on the screen to produce a *composite isoclinic pattern*. The directions of the principal stresses along any one of these isoclinics corresponds to the planes of the polarizer and analyser at which that isoclinic was produced. It is therefore possible to construct a series of lines which indicate the directions of the principal tensile and principal compressive stresses throughout the solid. It should be noted that such a stress pattern indicates only the directions of the principal stresses: it gives no indication, either relative or absolute, of the magnitude of these stresses.



Text-fig. 2. The apparatus used in stress analysis of plastic models of bone sections by the photoelastic method. *A* represents a light source producing a wide parallel beam; *BB* crossed polaroid plates; *C* the plastic model; *DD* a clamp by which external forces can be applied to the model; and *E* a ground-glass screen.

Stress analysis in bones

In adapting this photoelastic method to the stress analysis of a bone, a series of plane, $\frac{1}{4}$ in. thick sections of the bone were prepared. Life-size models of these sections were then made in $\frac{1}{4}$ in. Perspex sheet. It will be evident that these models were only approximate reproductions of the original sections for it was impossible to reproduce in them the minute details of bone structure. The compacta and spongiosa both participate in the transmission of the stresses within a bone, and for that reason both were represented by solid Perspex. A medullary cavity was simulated by a corresponding cavity cut in the plastic model. However, when a model in this form was subjected to external force it was found that the distortion of the plastic on either side of the marrow cavity was quite unlike that occurring in the complete bone, because the controlling effect of the bone on either side of the section was lacking. This difficulty was overcome by fixing $\frac{1}{8}$ in. sheets of plastic on either side of that part of the model containing the marrow cavity. These plates transmitted very little of the stress when the model was subjected to external forces but successfully prevented any abnormal distortion. The external forces to which these plastic models were subjected simulated as closely as possible in kind, magnitude and direction, those acting on the region of bone included in the original section. Compressive forces were applied directly to the regions representing the articular surfaces. Tensile stresses, on the other hand, were applied to extensions of the model representing the muscle or ligament concerned. These extensions were of considerable length so that the local effects of the method of application of the force did not affect the region of the model itself. Pl. 1, fig. 7, shows a plastic model of a vertical section of the tibia passing through the tuberosity and the lateral condyle. The extension from the region of the tuberosity represents the ligamentum patellae.

OBSERVATIONS

The calcaneus

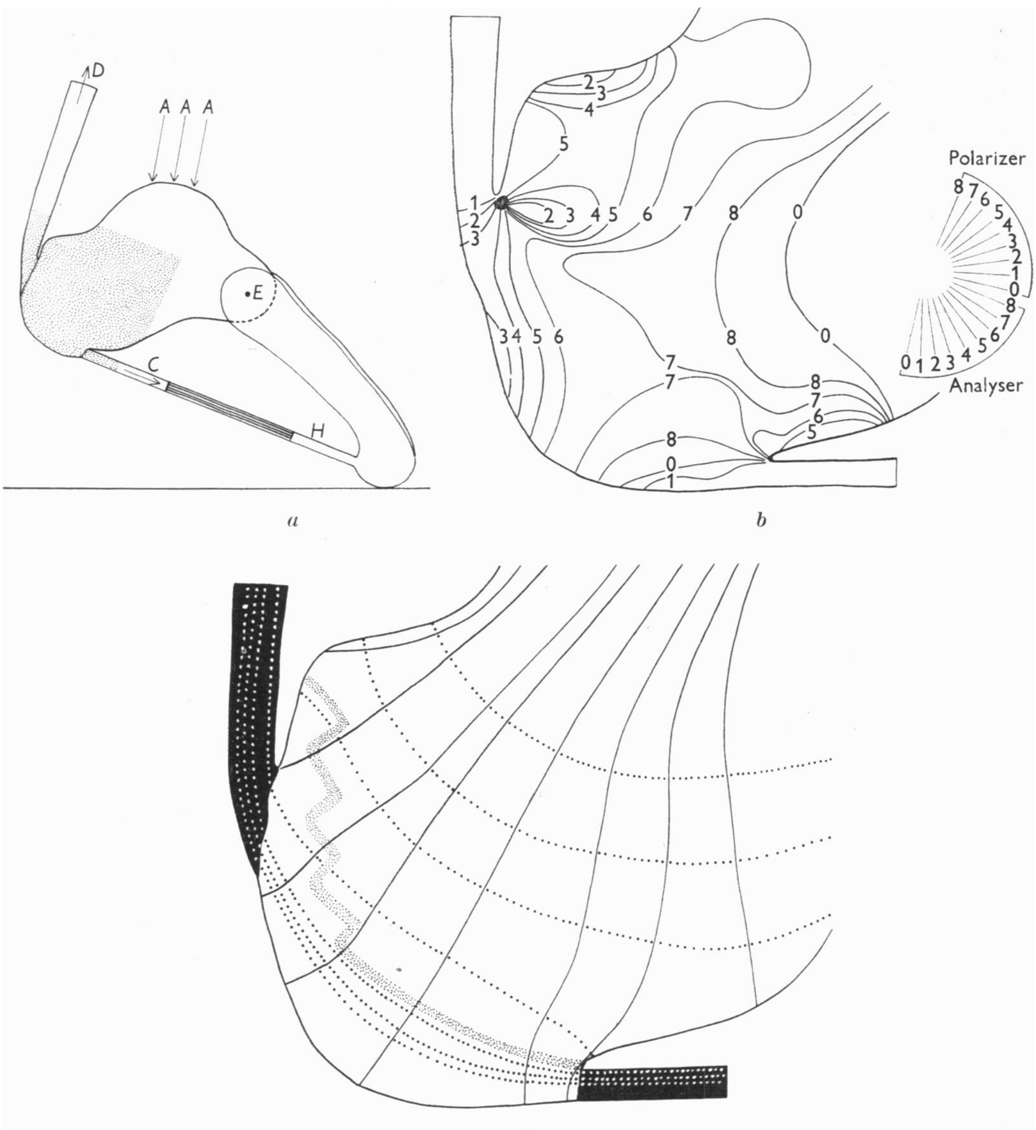
The single epiphysis of the calcaneus covers the greater part—from the whole to the lower three quarters—of the posterior surface, and extends forwards on to the inferior surface to include the whole of the medial and lateral processes of the tuberosity. The form of the epiphysial plate which separates this epiphysis from the body of the bone varies in minor details in different individuals but the common form is illustrated in Pl. 1, fig. 1. The central and lower parts follow a gentle and nearly continuous curve. On the other hand, the upper part, at and above the attachment of the tendo calcaneus, is in the form of a series of steps.

Two sets of structures are attached to the epiphysis of the calcaneus. The tendo calcaneus is inserted into the posterior surface while the superficial stratum of the plantar muscles and the central part of the plantar aponeurosis are attached to the medial and lateral processes of the tuberosity (Pl. 1, fig. 2).

The plastic model which was used in the stress analysis of the calcaneus conformed in outline to a sagittal section of the bones of the foot. It is shown diagrammatically in Text-fig. 3*a*. The model consisted of two parts, a single sheet representing the hind foot and two identical sheets, fused anteriorly, representing the forefoot. These parts were joined by a common axle at *E*. The extension *D* represented the tendo calcaneus, whereas the extensions *C* and *H* were joined by strong cord to simulate the plantar structures attached to the epiphysis. The stippled region indicates the area in which the stresses were analysed.

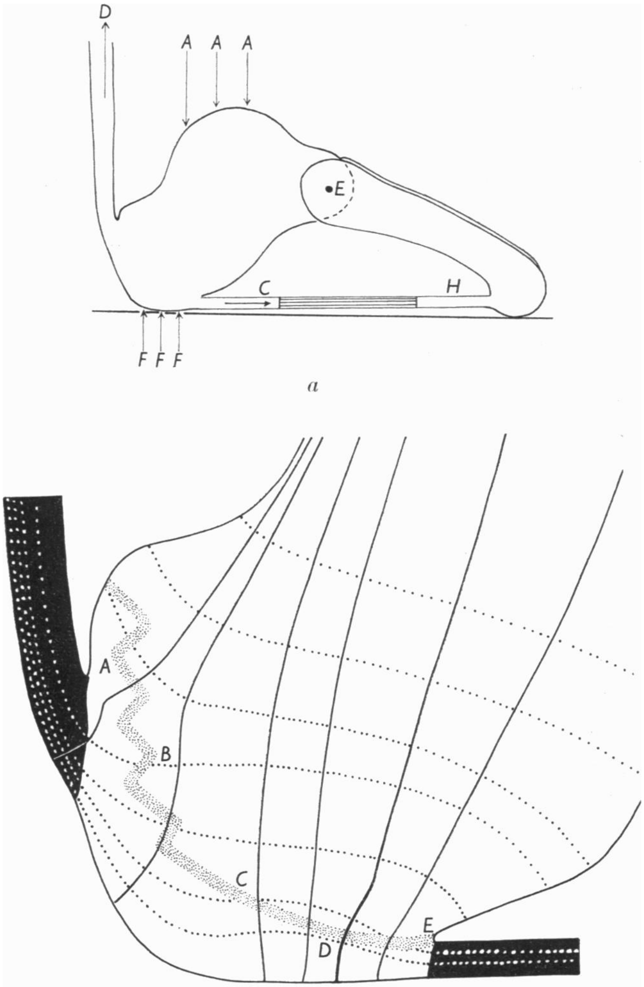
During activity the calcaneus is subjected to external forces in two common circumstances, and these were considered separately. During the latter part of each step in walking and running, contraction of the triceps surae lifts the heel from the ground and delivers an upward and forward thrust to the body, the weight of which acts downwards on the upper surface of the calcaneus. Furthermore, as the longitudinal arch flattens under body weight, and the toes are extended by plantar flexion at the talocrural (ankle) joint (Hicks, 1951), a tension is created in the plantar tissues which stabilises the position of the calcaneus. To simulate these forces the anterior part of the model rested on a rigid surface (Text-fig. 3*a*), a downward and slightly backward force was applied at *AAA* and an upward and slightly forward force at *D*. In these circumstances the stabilizing tension in the extension *C* occurred automatically.

The composite isoclinic pattern which occurred in the model under these conditions together with the relevant planes of the polarizer and analyser are shown in Text-fig. 3*b*. From this the stress pattern in Text-fig. 3*c* was constructed. The principal compressive stresses, indicated by solid lines, extend downwards and backwards through the body of the calcaneus and flare out to be distributed uniformly along



Text-fig. 3. Stress analysis of calcaneus in the weight-bearing foot with the heel raised. (*a*) Plastic model of sagittal section of foot. (*b*) Composite isoclinic pattern. Numbers indicate the planes of the polarizer and analyser at which the isoclinics were produced. (*c*) Stress pattern in calcaneus. Principal compressive stresses indicated by solid lines; principal tensile stresses indicated by interrupted lines. Black areas represent soft tissues; stippled zone represents epiphysial plate.

the posterior and inferior surfaces of the bone to which they bear an orthogonal relationship. The principal tensile stresses, indicated by interrupted lines, cross the compressive lines at right angles. Some are confined to the bone, but others, particularly those in the region of the epiphysis, are continuous with the principal tensile stresses operating in the tendo calcaneus and the plantar tissues. The stippled



Text-fig. 4. Stress analysis of calcaneus in the weight-bearing foot with the heel on the ground. (*a*) Plastic model of sagittal section of foot. (*b*) Stress pattern in calcaneus. Principal compressive stresses solid; principal tensile stresses interrupted. Black areas represent soft tissues; stippled zone represents epiphysial plate.

band in Text-fig. 3*c* represents an epiphysial plate similar in form to that in Pl. 1, fig. 1. In its lower part it runs parallel to the direction of the principal tensile stresses, and as a result there is no tendency for shear stress to displace the corresponding part of the epiphysis on the diaphysis. However, if the epiphysial plate were to continue along the same trajectory it would run into the attachment of the tendo calcaneus. And while this of itself would carry no disadvantage it would mean that the upper part of the posterior surface of the calcaneus would lack an epiphvsis. The steps which characterize the upper part of the epiphysial plate lie parallel in turn to the directions of the principal compressive and principal tensile stresses. Thus although shear stress operates between the epiphysis and diaphysis at each bend in the plate, the greater part is free of such stress. An epiphysial plate of this form can therefore be regarded as conforming to the growth requirements of the calcaneus, in so far as it covers the greater part of its posterior surface, and as achieving maximum stability between the epiphysis and diaphysis, by reducing shear stress between these parts to a minimum.

The calcaneus is also subjected to external forces during standing and in the early part of the supporting (stance) phase of walking. In these circumstances body weight acts downwards on the upper surface of the bone and the contraction of the triceps surae which is necessary to stabilize the centre of gravity of the body over the talocrural joint, acts upwards from the posterior surface. The force of body weight causes two reactive forces. That of the ground acts upwards through the tuberosity of the calcaneus and the tension in the plantar tissues which is due to depression of the longitudinal arch acts forwards from the same region. To simulate these forces (Text-fig. 4*a*) the same plastic model as in the previous experiment rested with the metatarsal head and the heel on a rigid horizontal surface. A downward force was applied at *AAA* and an upward force at *D*. The reactive forces at *C* and at *FFF* then occurred automatically. The stress pattern operating in the calcaneus in these circumstances is illustrated in Text-fig. 4*b*. In comparison to the stress pattern in Text-fig. 3*c* the solid lines of principal compressive stress are more vertical and instead of diverging to a uniform distribution around the posterior and inferior surfaces, the majority converge on the area of ground reaction in the region of the tuberosity of the calcaneus. As a result of this redisposition of the compressive stresses the interrupted lines of principal tensile stress bend more acutely forwards as they enter the bone from the tendo calcaneus and subsequently follow a more horizontal course. The stippled band in Text-fig. 4*b* represents the same epiphysial plate as that illustrated in Text-fig. 3*c*. It is evident that under these conditions the strict conformity between the plate and the stress pattern seen in Text-fig. 3*c* is present only in the regions *A* and *D*. At *B* and *C* shear stress tends to displace the epiphysis upwards whereas at *E* a similar stress tends to displace it forwards. However, the greatest stresses in the calcaneus in these circumstances are the compressive stresses acting across the lower part of the epiphysial plate on to the tuberosity. In this region there is no shear stress at *D* and opposite shear stresses at *C* and *E*. Consequently, despite the lack of total conformity between the epiphysial plate and the stress pattern, the relationship between the epiphysis and the body of the calcaneus during standing is still one of considerable stability.

Because the body of the calcaneus consists mainly of spongy bone with only a thin covering of compact tissue, the trabecular pattern can be readily seen in a lateral radiograph. It is widely held that these trabeculae conform to the directions of the principal stresses occurring in the bone when the heel is raised during walking and running (Morton, 1935). The relationship of these trabeculae to the epiphysial plates in Pl. 1, fig. 1, and to the principal stresses in Text-fig. 3*c* confirms this view. However, when the trabecular pattern is compared with the stress diagram characteristic of standing (Text-fig. 4*b*) it is evident that the pattern does not conform to the stresses operative in that phase of activity.

Thus both the internal trabeculae and the epiphysial plate in the calcaneus are so disposed that they give maximum stability when the calcaneus is affected by the greatest forces, that is when the triceps surae raises the heel during walking and running. On the other hand, neither the trabeculae nor the epiphysial plate are so placed that they give maximum stability during standing, or when the foot is flat on the ground during walking.

The proximal end of the tibia

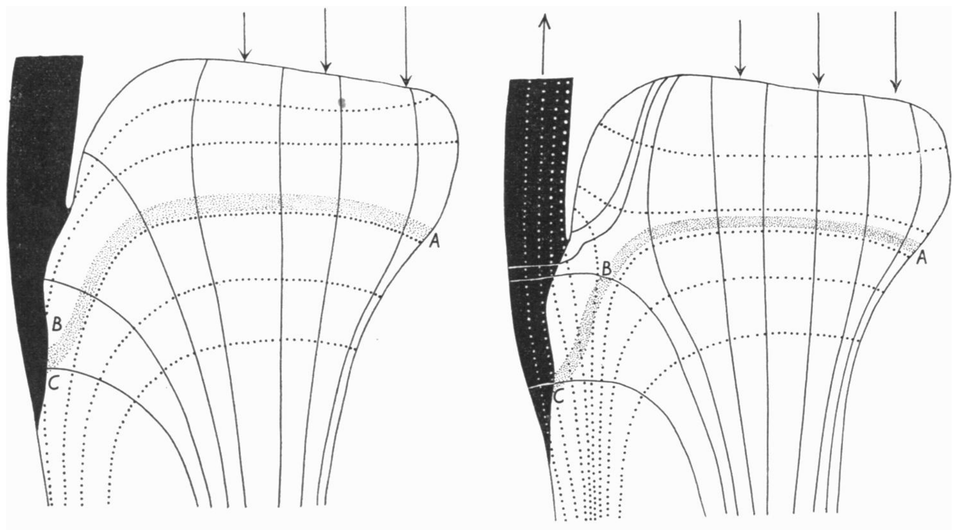
The form of the proximal epiphysial plate of the tibia can be visualized from the distal surface of the proximal epiphysis which is illustrated in Pl. 1, fig. 3. That part of the plate beneath the medial condyle (*A*) is flat and inclines medially and slightly downwards. Beneath the lateral condyle (*B*) it is convex upwards and slopes downwards and laterally. The medial and lateral condylar parts are directly continuous below the intercondylar eminence (*C*) but beneath the anterior and posterior intercondylar areas (*D* and *E*) the plate diverges in marked convexities towards the diaphysis.

The anterior part of the epiphysial plate (Pl. 1, fig. 4) turns sharply and runs downwards and slightly forwards between the anterior process of the epiphysis and the diaphysis. Finally it inclines towards the anterior surface of the tibia which it reaches at the lower part of the tuberosity. This part of the epiphysial plate is intimately associated with the ligamentum patellae. It has been stated (Last, 1959) that this tendon is inserted entirely into the epiphysis. However, the majority of authors agree that although the posterior fibres of the tendon are inserted into the anterior process of the epiphysis, the most anterior fibres continue over the epiphysial plate and are inserted into the anterior border of the diaphysis. This view is confirmed by examination of the newborn specimen in Pl. 1, fig. 5. The epiphysial plate at the proximal end of the tibia shows certain structural features which were originally described by Lewis (1958). The whole of that part beneath the condyles and the upper third of that part deep to the anterior process of the epiphysis has the cartilaginous structure typical of most epiphysial plates. On the other hand, the lower two-thirds of the anterior process of the epiphysis is separated from the diaphysis by dense fibrous tissue (Pl. 1, fig. 6). The collagen fibres in this tissue show a well marked orientation, running oblique to the plane of the epiphysial plate, but in alignment with the fibres of the ligamentum patellae. This structural differentiation between the anterior and posterior parts of the proximal epiphysial plate of the tibia is not peculiar to man. It occurs in the ox tibia, and the same structure has been described in the rabbit by Lacroix (1951) and in the rat by McLean & Bloom (1940).

Ossification begins in the main part of the epiphysis at or about the time of birth and spreads centrifugally. Up to the age of 10 years the anterior process is cartilaginous, but it is subsequently ossified either by an extension from the original centre or by the formation of a new centre which soon fuses with the original.

Two sections of the tibia were chosen for stress analysis. Each traversed one of the characteristic features of the epiphysial plate and was so placed that suitable external forces could be readily applied. The distribution of the principal stresses in these sections was studied in the two phases of normal activity in which the greatest external forces act on the bone, namely in standing and in the supporting (stance) phase of walking and running.

The first section lay in a vertical plane extending from the tuberosity backwards and laterally through the lateral condyle, and the plastic model on which analysis was made (Pl. 1, fig. 7) carried an extension representing the ligamentum patellae. In standing the quadriceps femoris muscle is inactive and body weight acts downwards from femur to tibia. To simulate the conditions in standing therefore, the



Text-fig. 5. Stress analysis of the proximal end of the tibia. (*a*) In standing. (*b*) In walking and running. Black areas represent the ligamentum patellae; stippled zones represent epiphysial plates. Principal compressive stresses solid; principal tensile stresses interrupted. Arrows indicate applied forces.

distal end of the model was supported on a rigid surface which conformed in shape to the trochlea of the talus, and a downward force was applied to the lateral condyle. The resulting stress pattern is shown in Text-fig. 5*a*.

Because of the retroversion present in its upper end, the tibia is subjected during weight bearing to a combination of axial compression and forward bending. Consequently the principal compressive stresses, indicated by solid lines, extend up the posterior two-thirds or so of the tibial shaft. The majority continue to the lateral condyle, but those placed most anteriorly in the shaft turn forwards to reach the anterior surface of the bone in the region of the tuberosity. The principal tensile stresses, indicated by the interrupted lines, extend along the anterior third or so of the shaft. As they reach the region of the tuberosity, however, they turn backwards below the lateral condyle and, crossing the directions of the compressive stresses at right angles, they reach the posterior surface of the bone.

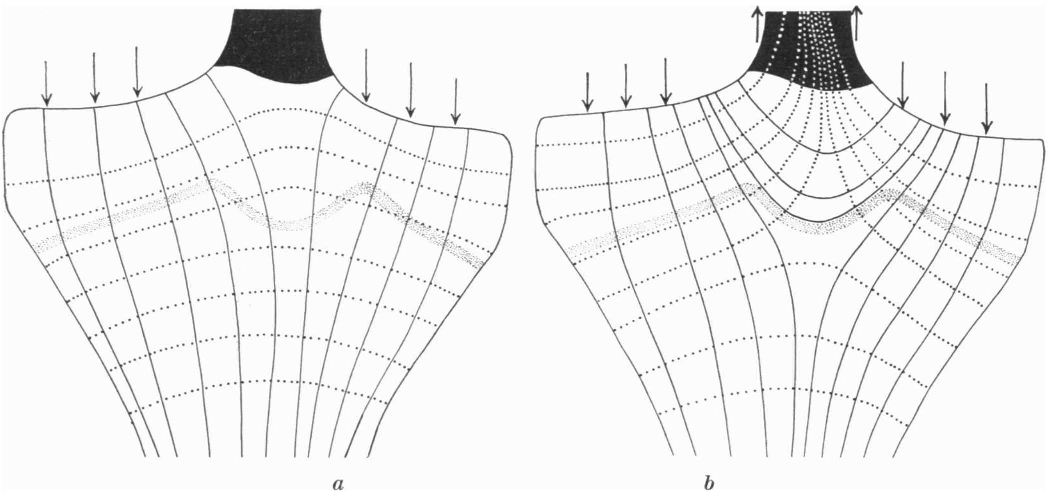
The stippled band in Text-fig. 5*a* indicates the position of an epiphysial plate of the form shown in Pl. 1, fig. 4. It is evident that from *A* to *B* the plate is very closely related to the lines of principal tensile stress. During weight bearing therefore this part is compressed between the epiphysis and diaphysis but is not subjected to shear stress. The part *BC* of the epiphysial plate is usually irregular in form, but in general it is oblique to both the principal compressive and the principal tensile stresses, and consequently experiences a mild shear stress which tends to displace the corresponding part of the epiphysis upwards and backwards on the diaphysis.

To simulate the external forces operating on the same section during the supporting phase of walking or running, the distal end of the model was supported as before, a downward force was applied to the lateral condyle and an upward force of similar magnitude was applied to the extension representing the ligamentum patellae. The resulting stress pattern is shown in Text-fig. 5*b*. Of the three sets of compressive stresses one extends from the posterior part of the shaft to the lateral condyle, a second from the middle of the shaft to the tuberosity and a third from the anterior part of the condyle to the upper part of the tuberosity. Similarly, there are three sets of tensile stresses. One extends from the anterior border of the tibia, through the tuberosity into the ligamentum patellae. The second arises from the same region of the shaft but turns backwards beneath the lateral condyle to reach the posterior surface of the bone, and the third set runs horizontally from the anterior to the posterior surface of the lateral condyle.

The stippled band in Text-fig. 5*b* represents the same epiphysial plate as that indicated in Text-fig. 5*a*. The part of the plate *AB*—that is the segment beneath the lateral condyle and that between the upper third of the anterior epiphysial process and the diaphysis—lies parallel to the lines of principal tensile stress. In walking and running this part is therefore compressed between the epiphysis and the diaphysis but is not subjected to shear stress. On the other hand, the part of the plate *BC* is oblique to both the principal compressive and principal tensile stresses, and it is evident that the large tensile stresses in the ligamentum patellae act obliquely across it. If this part of the epiphysial plate consisted of a rigid solid it would obviously be subjected to a severe shear stress tending to displace the anterior epiphysial process upwards and backwards on the diaphysis. However, comparison of Text-fig. 5*b* with Pl. 1, figs. 5 and 6, shows that this part of the epiphysial plate is identical with the part which consists entirely of collagen fibres. Moreover, it is evident that although the epiphysial plate itself is oblique to the principal stresses the collagen fibres of which it is composed are aligned with the principal tensile stresses and can consequently transmit these stresses between the epiphysis and the diaphysis. Thus here the stability of the epiphysial plate must be considered in two parts. The stability of the part *AB* depends on its orthogonal relationship to the stress pattern, whereas that of the part *BC* depends on the alignment of the constituent collagen fibres with the principal tensile stresses.

The second section of the tibia which was subjected to stress analysis lay in a coronal plane and traversed successively the posterior intercondylar area, the corresponding diaphysial deflexion of the epiphysial plate (*E* in Pl. 1, fig. 3) and the posterior part of the shaft. The section was directly associated with the tibial attachment of the posterior cruciate ligament, and this was therefore represented by a suitable extension in the plastic model (Text-fig. 6). The exact condition of the cruciate ligaments during different phases of activity must still be regarded as controversial, but it is now generally agreed (Brantigan & Voshell, 1941; De Palma, 1954) that some tension exists in both ligaments in all positions of the knee joint. The following stress analysis suggests that tension in the posterior cruciate ligament is an essential factor in the determination of the form of the subjacent epiphysial plate.

When the plastic model was subjected simply to longitudinal compression between the two condyles and the distal end, the stress pattern took the form indicated in Text-fig. 6*a*. The solid compressive stresses act upwards from the shaft on to the medial and lateral condyles, while the interrupted tensile stresses act along lines which traverse the bone from side to side. Immediately below the posterior cruciate ligament these lines of tensile stress are convex upwards.



Text-fig. 6. Stress analysis of the proximal end of the tibia. (*a*) With no tension in the posterior cruciate ligament. (*b*) With tension in the posterior cruciate ligament. Black areas represent posterior cruciate ligament; stippled zones represent epiphysial plates. Principal compressive stresses solid; principal tensile stresses interrupted. Arrows indicate applied forces.

The stippled band in Text-fig. 6*a* represents the outline of a typical epiphysial plate in the plane of the section. It is evident that in relationship to such a stress pattern that part of the epiphysial plate which is deflected towards the diaphysis is oblique to the principal stresses and as such would be subjected to a considerable shear stress.

Text-fig. 6*b* shows the stress pattern which occurred when, in addition to longitudinal compression between the condyles and the distal end, the pull of the posterior cruciate ligament was simulated by applying an upward force to the corresponding extension. Compressive stresses still act upwards from the shaft and diverge to reach the medial and lateral condyles. Now, however, a new compressive system operates between the central parts of the two condyles along lines which are convex downwards. In the lower part of the diagram the lines of tensile stress cross the shaft from side to side. Above, however, they are diverted upwards from either side into the posterior cruciate extension. If the same epiphysial plate is again indicated by a stippled band, it is apparent that it now conforms much more closely to the stress pattern. On either side the plate follows the lines of tensile stress and is consequently compressed but free of shear stress. However, if the plate continued in these directions it would be carried into the posterior intercondylar area. Centrally, therefore, it is diverted abruptly into the lines of compressive stress where it is again free of shear stress. In this way shear stress between the epiphysis and diaphysis is restricted to the two small regions where the plate shifts from compressive to tensile trajectories.

Thus it is considered that, provided there is tension in the posterior cruciate ligament, the deflexion of the epiphysial plate towards the diaphysis, beneath the ligament, contributes to the stability of the epiphysis on the diaphysis. Moreover, it is suggested that similar factors are associated with the less prominent diaphysial deflexion of the epiphysial plate beneath the anterior cruciate ligament though experimental proof of this is made difficult by the proximity of this deflexion to the tensile region of the anterior border of the tibia.

The distal end of the femur

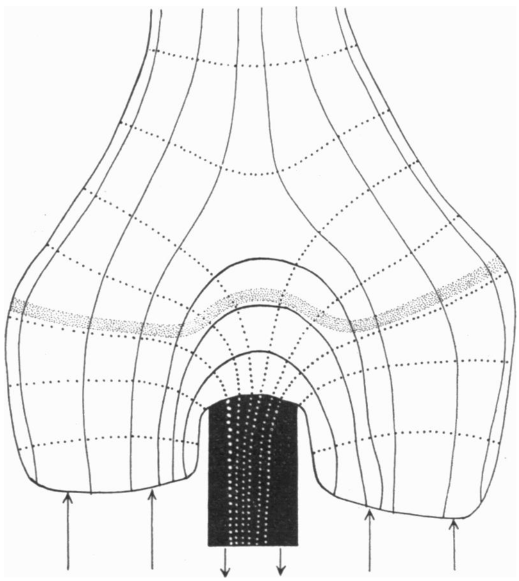
The form of the epiphysial plate in this region is most readily appreciated by examination of the proximal surface of a separated distal femoral epiphysis at an age approaching that of fusion (Pl. 1, fig. 8). The posterior half of this surface is concave on either side, but these two concavities are separated by a blunt ridge which overlies the attachment of the cruciate ligaments in the intercondylar fossa. In the region of the blunt ridge there is a corresponding deflexion of the epiphysial plate towards the diaphysis which, in its position and its relationship to the cruciate ligaments, is similar to those already noted in the proximal epiphysial plate of the tibia. The anterior half of the proximal surface of the epiphysis is gently concave from before backwards except at its anterior edge which is convex. It is separated from the posterior half by a rather sharp transverse ridge. These features of the epiphysial plate can be visualized in suitable radiographs. (Pl. 1, fig 9; Pl. 2, fig. 1).

It is evident from the form of the bone that when the femur transmits body weight, the shaft bends forwards and laterally so that the anterior and lateral aspects are subjected to longitudinal tensile stresses while the posterior and medial aspects experience longitudinal compression. This has been confirmed by Pederson, Evans & Lissner (1949) using the stress coat technique.

The distribution of the principal stresses in the distal end of the femur has been studied in plastic models of two sections. The first of these was a coronal section which extended from the middle of the linea aspera to the medial and lateral condyles, traversing in its path the bone deep to the popliteal surface, the posterior half of the epiphysial plate and the intercondylar fossa. The diagram of the distal part of this model in Text-fig. 7 shows the extension (in black) which represented the attachment of the cruciate ligaments in the intercondylar region.

It is evident that in any weight-bearing activity the forces affecting this section will consist of compressive forces acting on the proximal end and the two condyles, together with a tensile force pulling downwards on the cruciate ligaments.

The distribution of the principal stresses in the section, in these circumstances, is shown in Text-fig. 7 and its similarity to the stress pattern in a coronal section through the tibia (Text-fig. 6*b*) is readily apparent. The main compression stresses (solid) act from the shaft on to the condyles while a subsidiary compressive system operates between the central parts of the articular surfaces. In the shaft and in the lower parts of the condyles the lines of tensile stress (interrupted) are more or less transversely disposed but in the intervening region they are diverted downwards to the intercondylar fossa and through it into the cruciate ligaments. It is of interest that Barnett (personal communication) was able to demonstrate trabeculae in the distal end of an adult femur which conformed to the subsidiary system of compressive stresses operating between the condyles in Text-fig. 7.

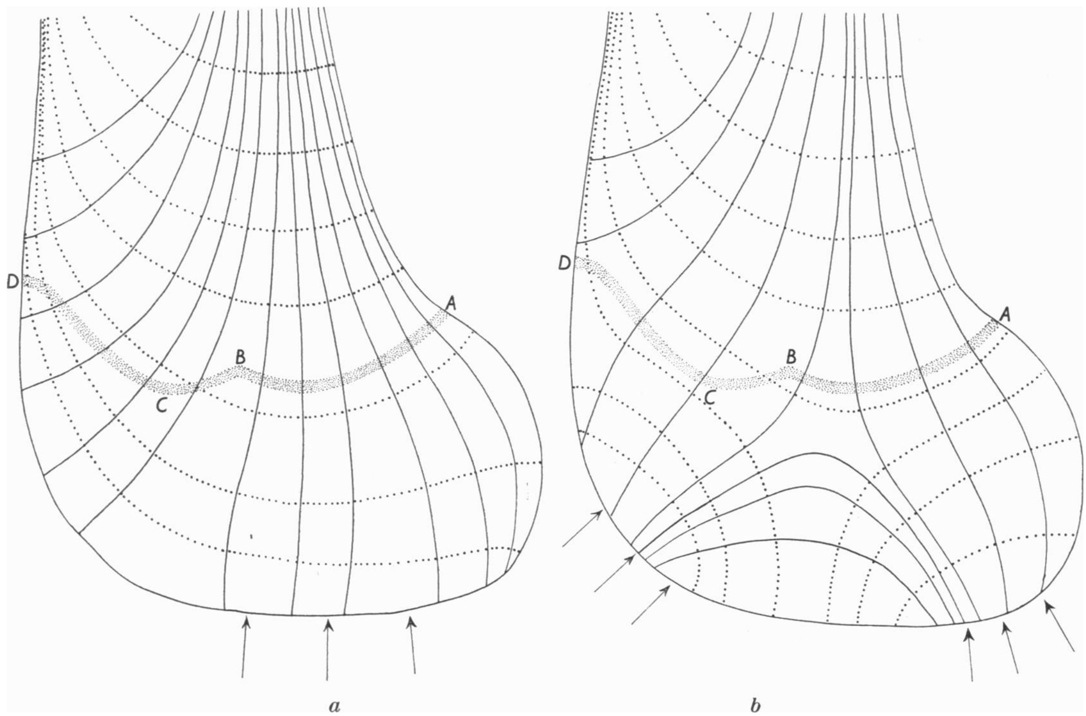


Text-fig. 7. Stress analysis of the distal end of the femur. Black area represents cruciate ligaments; stippled zone represents epiphysial plate. Principal compressive stresses solid; principal tensile stresses interrupted. Arrows indicate applied forces.

The stippled band, representing a typical epiphysial plate, has a relationship to the principal stresses which is essentially similar to that already observed in the proximal end of the tibia (Text-fig. 6*b*). On either side it lies parallel to the lines of tensile stress, centrally it conforms to the lines of compressive stress, and only in the intervening regions is it subjected to shear stress.

The second model was a replica of a vertical section which traversed the patellar articular surface and the lateral condyle and continued upwards through the shaft to the region of the greater trochanter. The forces affecting such a section vary in different circumstances. In standing the section is subjected to a compressive force between the proximal end of the model and the anterior part of the condylar facet (Text-fig. 8*a*). In the supporting phase of walking and running, on the other hand, the section is subjected to a greater longitudinal compressive force, which is applied somewhat farther back on the condylar facet, while in addition, contraction of the quadriceps femoris muscle exerts an upward and backward force on the patellar surface (Text-fig. 8*b*).

When the forces operative in standing are simulated, the stress pattern is typical of a pillar subjected to a combination of axial compression and bending (Text-fig. 8*a*). The compressive stresses (solid lines) are aggregated in the posterior half of the shaft. Entering the distal end of the bone the majority diverge to reach the anterior part of the condylar facet while the more anterior trajectories turn forwards to reach the anterior surface of the shaft and the patellar surface. The tensile stresses (interrupted



Text-fig. 8. Stress analysis of the distal end of the femur. (*a*) In standing. (*b*) In walking or running. Stippled zones represent epiphysial plates. Principal compressive stresses solid; principal tensile stresses interrupted. Arrows indicate applied forces.

lines) occupy the anterior aspect of the shaft, but as they approach the distal end they turn backwards to cross the compressive trajectories at right angles and reach the posterior surfaces of the shaft and the lateral condyle.

In walking and running the application of force to the patellar surface brings about a change in the stress pattern (Text-fig. 8*b*). The main lines of compressive stress still occupy the posterior part of the shaft, but as they approach the distal end of the bone they divide into three distinct systems. The most posterior trajectories turn somewhat backwards to reach a comparatively small area at the middle of the condylar facet, the most anterior trajectories turn forwards to the anterior aspect of the shaft, while the middle group run forwards and downwards before converging on the middle of the patellar surface. An additional compressive system operates between the patellar and condylar facets along lines which are convex upwards. There are three corresponding sets of tensile trajectories. Those arising from the anterior part of the shaft sweep backwards to the posterior surface. The other two groups arise respectively from the upper parts of the patellar and condylar facets. As they approach one another, they turn downwards and converge on the interval between the patellar and condylar facets.

The stippled bands in Text-figs. 8*a* and *b* represent epiphysial plates of typical form. In each case the posterior part of the plate (*AB*) is concave upwards and conforms closely to the tensile trajectories in the region. On the other hand, the anterior part of the plate (*CD*) does not conform exactly to the tensile trajectories in the neighbourhood in either case. It is suggested that the form of this part represents a compromise between the different mechanical demands of the two stress patterns commonly active in the region. The small central part (*BC*) lies on the anterior slope of the transverse ridge on the proximal surface of the epiphysis (Pl. 1, fig. 8), and it is evident that it is oblique to both the compressive and tensile trajectories. It is further suggested that this part of the plate represents a 'slip' from one tensile trajectory to another, and that by virtue of this slip the posterior part of the plate is kept above the condylar articular surface, while the anterior part is kept comparatively low down the anterior aspect of the shaft.

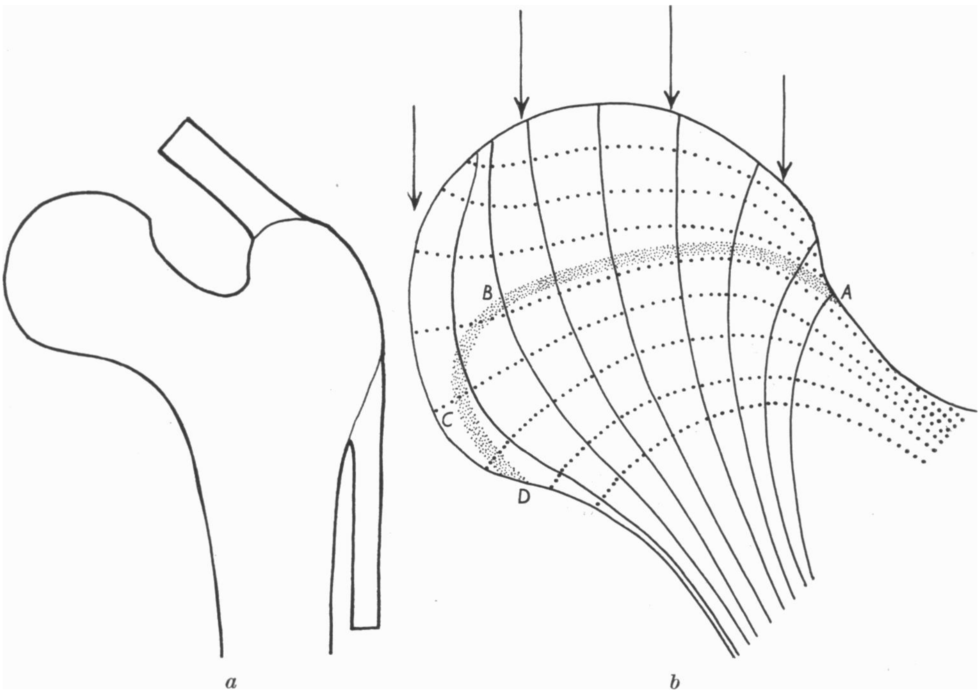
Comparing Text-figs. 8*a* and *b* it is evident that the stress patterns in the two phases of activity which have been considered are essentially similar in the shaft but are markedly different in the distal end of the bone. The epiphysial plate lies at the lower limit of similarity, that is, in the lowest position in which a compromise between the mechanical demands of the two stress patterns can be readily achieved.

The proximal end of the femur

The shape of the epiphysial plate at the head of the femur is very widely misrepresented in both anatomical and orthopaedic texts. It has to be appreciated that although the form of a bony diaphysis always indicates the form of the related epiphysial plate, a bony epiphysis often gives no such indication until a short time before growth ceases.

At the proximal end of the femur, that part of the proximal surface of the diaphysis which is associated with the head, maintains a more or less constant form throughout development. Its form in coronal section at birth is shown in Pl. 2, fig. 2. From the junction between the trochanteric and the capital parts, the proximal surface of the diaphysis runs medially and slightly downwards in a gentle curve, convex upwards. Approaching the medial side of the femur, however, it bends acutely so that it eventually runs downwards and slightly laterally, to meet the surface of the neck at an acute angle. In adult life (Pl. 2, fig. 3) the proximal surface of the diaphysis, now indicated by the epiphysial scar, has a very similar form. The epiphysial scar in this figure can therefore be taken as indicating the outline of the epiphysial plate throughout postnatal development. The illusion of a straight epiphysial plate, so often seen in radiographs of young subjects (Pl. 2, fig. 5), is due to the fact that ossification has not yet extended into the lower part of the epiphysis. The similar illusion given by the epiphysial scar in radiographs of adults (Pl. 2, fig. 6) is due to the fact that this bony scar is only well developed in regions of strong compressive stress so that the lower and medial part is not usually visualized.

The relationships of this epiphysial plate to the articular surface of the femoral head is also frequently misrepresented. In its upper part the plate is separated from the capital articular cartilage by a non-articular zone. This separation is a fundamental feature of the region, for as Trueta (1957) has described, it is through the large foramina in the non-articular zone (Pl. 2, fig. 4) that the main blood supply to the head of the femur enters the bone. In its anterior, posterior and inferior parts the plate conforms to the articular margin.



Text-fig. 9. Stress analysis of the head of the femur. (*a*) Upper half of plastic model. Extensions represent vastus lateralis and the gluteus medius and minimum. (*b*) Stress pattern common to standing and to the supported phase of walking and running. Stippled zone represents epiphysial plate. Principal compressive stresses solid, principal tensile stresses interrupted.

The distribution of stress in the head of the femur during standing and during the supported phase of walking and running was studied in a coronal section passing through the head, the greater trochanter and the shaft of the bone. The plastic model of this section (Text-fig. 9*a*) carried two extensions representing the vastus lateralis and the gluteus medius and minimus. To simulate the forces operative in standing, compressive forces were applied to the upper half of the head and to the distal end of the model. On the other hand, to simulate the forces operative during the supported phase of walking or running, the same compressive forces were associated with tensile forces acting from and in the directions of the two extensions.

Despite the difference in the applied forces it was found that the stress patterns in the head of the femur were identical in the two phases of activity considered. It should be noted that although the stress patterns were found to be identical, estimation of the magnitudes of the stresses would have shown that they were very different. The common stress pattern is illustrated in Text-fig. 9*b*. It is essentially similar to the mathematical analyses of Meyer (1867) and Wolff (1870), and to the photoelastic analysis of Fessler (1957). The principal compressive stresses (solid) are aggregated at the medial side of the shaft. They diverge through the lower part of the neck and, passing upwards and medially through the head, reach the upper part of the capital articular surface. The principal tensile stresses (interrupted) spring from the lateral part of the shaft. Thereafter they run in smooth continuous curves which traverse first the junction between shaft and greater trochanter and then the upper part of the neck before diverging to reach the medial and inferior aspects of the head. The similarity between this stress pattern and the disposition of the bone trabeculae in a similar coronal section is well known.

The stippled band in Text-fig. 9*b* represents an epiphysial plate of typical form and position. Its more lateral horizontal part *AB* lies parallel to the principal tensile stresses. It is, therefore, free of shear stress, and body weight has no tendency to cause displacement of the corresponding parts of the epiphysis and diaphysis. Continuation of the epiphysial plate in a medial direction, along the same tensile trajectory, however, would carry it into the articular surface and, apparently to avoid this, the lower part of the plate (*BD*) turns downwards and laterally to reach the articular margin. As a result the segment (*CD*) comes to lie almost parallel to the principal compressive stresses and is therefore, like *AB*, practically free of shear stress. But the segment *BC* is necessarily oblique to both the principal compressive and principal tensile stresses and experiences a shear stress which tends to displace the femoral head downwards and medially on the neck.

Relation of growth process to stress

The observations described in the preceding sections strongly suggest that the greater parts of the epiphysial plates which have been considered are orientated parallel to one or other of the principal stresses which affect the region during normal activity. Moreover additional observations on the bones of the ox, taken in conjunction with the studies of Thomson (1902) and Barnett (personal communication), indicate that such a disposition of the epiphysial plates is probably a common characteristic of mammalian bones. On the other hand, the proliferating columns of cartilage cells which are characteristic of the diaphysial regions of epiphysial plates bear no direct relationship to the stress pattern which operates around them. On the contrary they are orientated in the direction of the bone growth which they create. In many situations the stress pattern itself has an orthogonal relationship to the direction of bone growth so that the cell columns lie at right angles to the plane of the epiphysial plate. But where this relationship does not exist the cell columns occupy an oblique position such as that illustrated in Pl. 2, fig. 7. The same association with growth rather than with stress is seen in the primary diaphysial bone trabeculae which form on the cartilage rods persisting after erosion of the cell columns (Pl. 2, fig. 8). It is only after these primary trabeculae have been in turn eroded and secondary trabeculae have been laid down at some distance from the epiphysial plate that structural alignment with the stress pattern is to be found.

Thus in any region in which an epiphysial plate is oblique to the direction of bone growth there is a zone of primary trabeculae, in the epiphysial extremity of the diaphysis, in which the structural elements are not aligned to the stress pattern of the part and are consequently exposed to a shear stress tending to displace the epiphysis on the diaphysis.

DISCUSSION

The photoelastic method, as it has been used in the present investigation, obviously involves certain approximations. First, the plastic models were not exact replicas of the bone sections, for it was impossible to reproduce the intricate trabeculae of the spongiosa. Nevertheless, it is considered that the simulation of the marrow cavity, described earlier, and the use of sections extending through the length of the bone were improvements on the method previously used by Fessler (1957). Secondly, only isolated sections were investigated and the effect of stresses in neighbouring regions was ignored. And thirdly, only the more important of the external forces acting on the actual bones were considered in planning the forces to be applied to the corresponding models. Consideration of all the minor forces which operate on the bones in normal activity would undoubtedly have caused minor changes in the stress pattern.

However, despite these several possible sources of error, the photoelastic method remains by far the most accurate of those available for the analysis of stress within structures of complicated form. Moreover, it is considered that the approximations, and the errors arising from them, were not of sufficient magnitude to invalidate the general results of the investigation.

The observations reported in the preceding sections strongly support the view that the disposition of epiphysial plates is in harmony with the stress pattern or patterns characteristic of normal activity. Each plate tends to lie parallel to one or other of the principal stresses in the region so that shear stress between the epiphysis and the diaphysis is minimal. Furthermore, consideration of the plates at the proximal end of the tibia and at the head of the femur (Pl. 1, fig. 5; Pl. 2, fig. 2) at birth shows that the characteristic form of each epiphysial plate tends to be established before anything but the most minor external forces can operate. The disposition of the plates must therefore be regarded as inherent in the growth pattern of each individual bone and not as being caused by the stress to which each plate will ultimately be subjected.

A relationship between epiphysial plates and stress has been noted by other authors. Thomson (1902) noted the similarity in the form of the distal femoral epiphysial plate in a large number of mammals and suggested that the irregular nature of the junction between the epiphysis and the diaphysis tended to prevent displacement between these parts during activity. Inman (1947) observed that the greater part of the epiphysial plate at the head of the femur in man lies at right angles to the main compressive trabeculae and concluded that this disposition avoided shear stress between the corresponding parts of the epiphysis and diaphysis. And more recently Barnett (personal communication) considered the relationship between the distal femoral epiphysis and the neighbouring bone trabeculae in the bear and concluded that the plate lay, in general, at right angles to the compressive stresses within the bone.

The present investigation, however, shows that epiphysial plates do not always lie at right angles to the compressive stresses and therefore parallel to tensile trajectories. Certainly, in regions of maximal compressive stress, this relationship usually holds true, but elsewhere, the plate may be related to either of the two principal stresses. In such regions the relationship seems to be determined by one or more of three factors. First, as Lacroix (1951) has observed, there is considerable mechanical advantage in the attachment of a muscle to the epiphysis of a bone rather than to its diaphysis, for in these circumstances its attachment is not required to move in relation to the bone surface during growth, and can consequently be of a stronger and more stable nature. It is suggested therefore that in some instances epiphysial plates pass along those principal stress trajectories which will place the attachments of strong postural muscles on the epiphyses rather than on the diaphyses of the bones concerned. Thus at the proximal end of the tibia the anterior part of the plate turns downwards so that a large part of the ligamentum patellae becomes attached to the epiphysis, and the advantage of this arrangement seems to outweigh the disadvantage of exposing the anterior part of the plate to a large tensile stress. Similarly, the epiphysial plate of the calcaneus turns forwards on to the inferior aspect of the bone and as a result both the triceps surae and the larger plantar muscles gain an attachment on the epiphysis.

The second factor which appears to determine the relationship of the epiphysial plate to stress is the disadvantage of an epiphysial plate running into either an articular surface or a bone surface at which longitudinal growth must occur. Thus at the head of the femur the epiphysial plate is parallel to the tensile trajectories in the region of maximal compressive stress, but continuation along the same trajectories would carry it into the articular surface. The acute bend which occurs in the medial part of the plate carries it to the articular margin (Text-fig. 9*b*). Similarly, at the distal end of the femur the epiphysial plate, as seen in coronal section (Text-fig. 7) is parallel to tensile trajectories in the regions of maximal compressive stress above the condyles. However, continuation along these trajectories would carry the plate to the bone surface in the intercondylar fossa and consequently the plate is diverted into compressive trajectories in its central part.

Thirdly, it seems probable that as far as growth is concerned there is a certain advantage in an epiphysial plate being approximately transverse to the long axis of the parent bone. In some situations the advantage of this arrangement may be outweighed by other considerations, as at the proximal end of the tibia and the head of the femur. However, it is suggested that the shift of the epiphysial plate at the distal end of the femur from one tensile trajectory in the posterior part of the bone, to a lower tensile trajectory in the anterior part (Text-fig. 8) is simply a measure which produces an approximately horizontal plate.

Those parts of epiphysial plates which lie parallel to tensile trajectories, and across which therefore compressive stress acts, have the well known microscopic appearance shown in Pl. 2, fig. 7. Those parts, such as the distal femoral plate above the intercondylar fossa, which lie parallel to compressive trajectories (Text-fig. 7) and are crossed by comparatively weak tensile stresses, have the same structure. On the other hand, in the one situation described in this account where an epiphysial plate is crossed by powerful tensile stresses, namely in the region of the tibial tuberosity, the plate consists not of cartilage but of collagen fibres orientated in the direction of the stress (Pl. 1, fig. 6). In the course of the present work other sites of fibrous regions in epiphysial plates have been noted and since their interest lies, not only in their orientation to stress, but also in their relation to longitudinal bone growth, they will be considered in detail in another paper. For the moment it can be said that the structure and position of the anterior part of the proximal tibial epiphysial plate are such that most of it has an orthogonal relationship to comparatively weak principal stresses during standing; in walking and running, on the other hand, although this part of the plate itself is not parallel to either of the principal stresses, the collagen fibres of which it consists are aligned with the strong tensile trajectories and withstand the pull of the quadriceps tendon.

SUMMARY

The relationship between the position and form of epiphysial plates and the stresses operating in the relevant bones during normal activity has been studied in the calcaneus, at the proximal end of the tibia, and at the distal end and head of the femur.

The epiphysial plates have been examined in microscopic sections, in dried immature and adult bones and in radiographs. The distribution of the principal stresses in selected sections of the relevant bones has been studied by the photoelastic method.

The results of the investigation suggest that there is a strong correlation between the disposition of the epiphysial plates and the related stress patterns. The greater parts of most epiphysial plates lie at right angles to principal compressive stresses and are consequently subjected to pure compression between epiphysis and diaphysis. The factors which appear to determine other relationships between certain parts of epiphysial plates and the stress pattern have been discussed.

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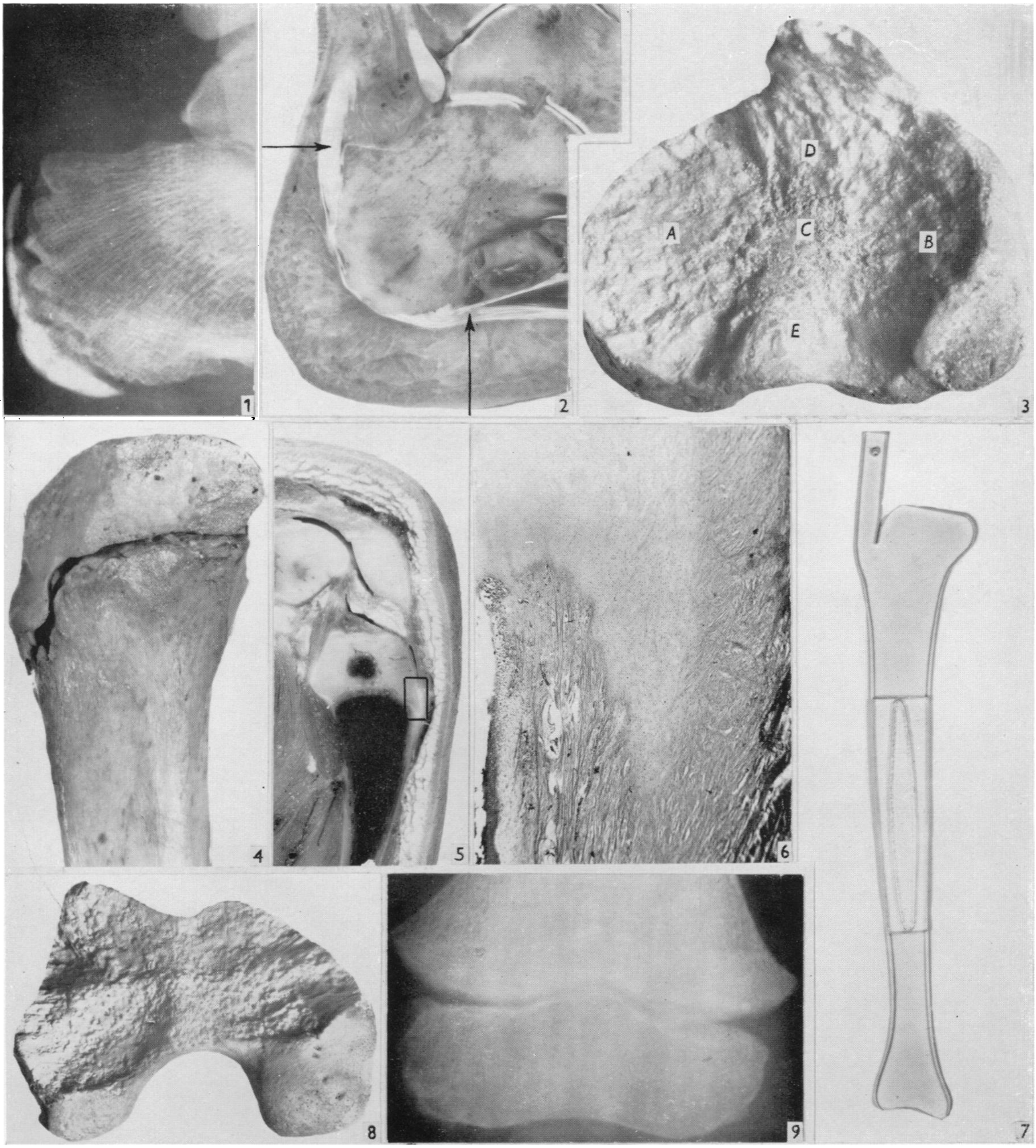
EXPLANATION OF PLATES

PLATE 1

Fig. 1. Lateral radiograph of posterior part of calcaneus at 14 years.
Fig. 2. Posterior part of sagittal section of adult foot. Arrows indicate tendo calcaneus and central part of plantar aponeurosis.
Fig. 3. Distal surface of proximal epiphysis of left tibia at about 18 years.
Fig. 4. Lateral aspect of upper end of left tibia at about 18 years.
Fig. 5. Sagittal section of knee joint and upper part of tibia at birth.
Fig. 6. The area indicated in fig. 5. On the right, the ligamentum patellae; lower left, the thin cortex of tibia; upper left, cartilaginous proximal tibial epiphysis with cartilaginous anterior epiphysial process passing downwards. H. & E. $\times 15$.
Fig. 7. Perspex model of $\frac{1}{4}$ in. vertical section of tibia traversing the tuberosity and the lateral condyle. Note cavity simulating medullary cavity, $\frac{1}{8}$ in. plates covering both sides of cavity, extension simulating ligamentum patellae.
Fig. 8. Proximal surface of distal epiphysis of left femur at about 18 years.
Fig. 9. Antero-posterior radiograph of lower end of femur at 13 years.

PLATE 2

Fig. 1. Lateral radiography of lower end of femur at 15 years.
Fig. 2. Coronal section of upper end of femur at birth. H. & E. $\times$ 2.
Fig. 3. Coronal section of upper end of adult femur. Undecalcified. Photograph by transmitted light.
Fig. 4. Distal surface of capital epiphysis of femur at about 17 years. Pointers indicate vascular foramina.
Fig. 5. Antero-posterior radiograph of upper end of femur at 4 years.
Fig. 6. Antero-posterior radiograph of upper end of adult femur.
Fig. 7. Sagittal section of distal end of femur of immature ox. Diaphysis above, epiphysis below. H. & E. $\times 2$.
Fig. 8. The area outlined in fig. 7. $\times 35$.



SMITH—RELATIONSHIP OF EPIPHYSIAL PLATES TO STRESS

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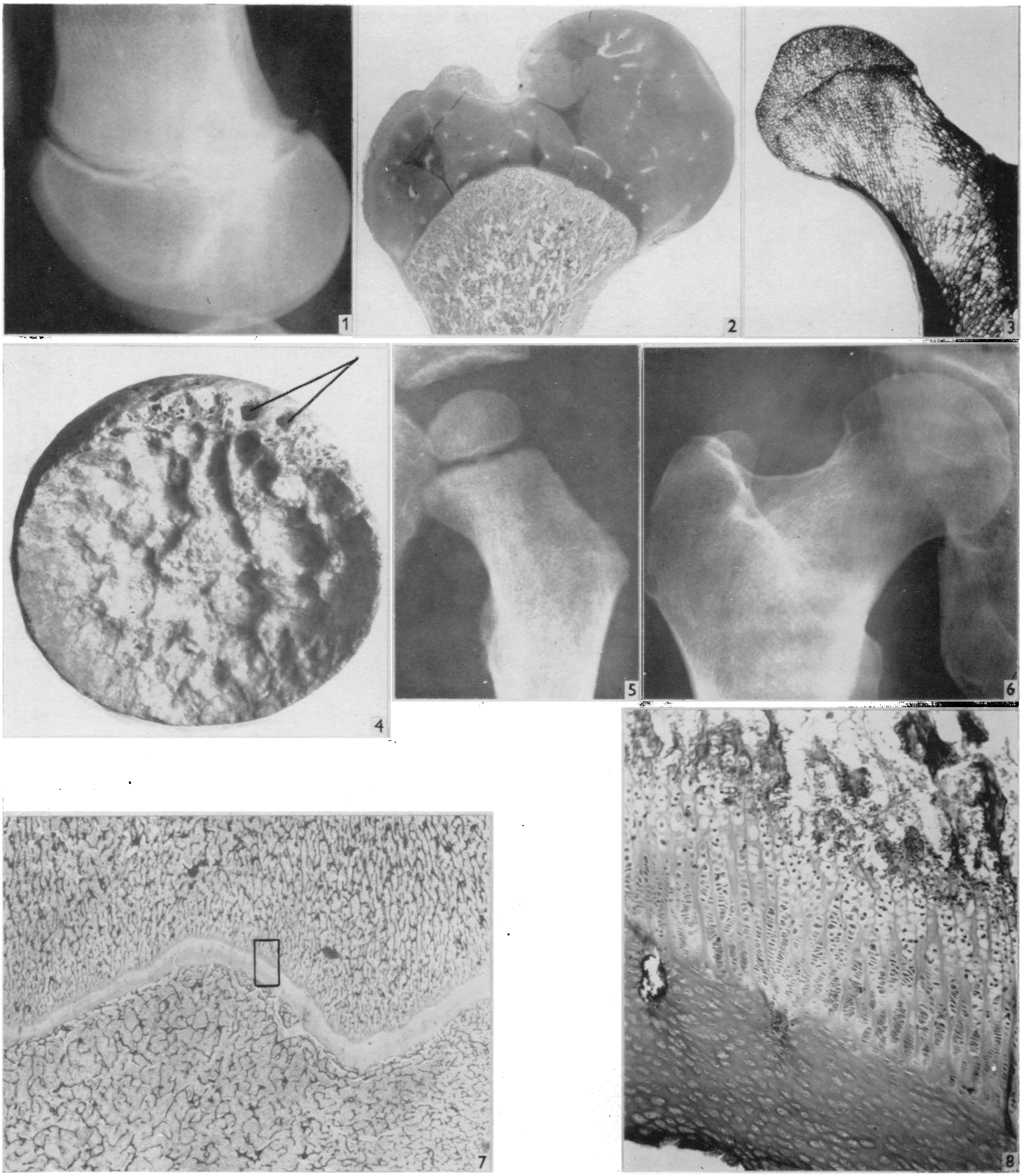

SMITH—RELATIONSHIP OF EPIPHYSIAL PLATES TO STRESS